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NASA Life Sciences Advanced Refrigerator/ Freezer Technology Assessment Results

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ABSTRACT

The NASA Lewis Research Center, through contract with Oceaneering Space Systems, is engaged in a project to develop advanced refrigerator/freezer (R/F) technologies for future Life and Biomedical Sciences space flight missions.

The first phase of the project, a technology assessment recently has been completed to identify the advanced refrigerator/freezer technologies needed and best suited to meet the requirements for the five R/F classifications specified by the researchers, to rank those technologies based on benefit and risk, and to recommend those which can be developed within this project. This paper presents the basis, the methodology, and results of the R/F technology assessment, and makes recommendations for the technology areas to be developed.

INTRODUCTION

To date, a limited number of small Refrigerator/Freezer (R/F) systems have been developed for space applications to support Life and Biomedical Sciences space missions (14 days or less) and operate in the temperature range of –20 to +4 °C. The Orbiter R/F (OR/F), which is about the size of the small refrigerators found in college dormitories, and the Life Science Laboratory Equipment (LSLE) R/F, which is about twice the size of the OR/F, have been developed for use on the Shuttle mid-deck and Space Lab, respectively. Variations of the OR/F have been cooled by CFC vapor compression and Stirling cycle coolers. However, since they were designed to meet some very difficult requirements for space, i.e. operate without gravity and to ensure crew safety, they tended to be complex, noisy, unreliable, and require excessive maintenance.

Current flight systems are cooled using solid-state thermoelectric (TE) devices, which eliminate the need for toxic fluids. They are quiet and vibration free, and have proved to be very reliable. However, the low efficiency TE coolers have limited cooling capacity. Frost accumulation in the storage space heat exchanger tends to reduce cooling capacity. An effective means for automatic frost removal, that operates reliably in space, has not yet been devised and defrosting requires manual assistance by the crew.

Future Life and Biomedical Science experiments are anticipated to last much longer; up to 90 days or more. To avoid spoilage, test specimens will have to be stored at much lower temperatures; down to near liquid nitrogen temperature (–196 °C). The number and types of samples to be stored are expected to increase, requiring larger storage volume and several storage temperatures. The research scientists have identified five freezer classifications needed for their space experiments. Frost management is expected to be even more of a problem. The low efficiency of the thermoelectric coolers precludes their practicality for larger cold volumes with temperature differentials greater than about 60 °C.

To address future Life and Biomedical Sciences space mission technology needs, NASA Lewis Research Center is conducting an Advanced R/F Technology Development Project [1], with Oceaneering Space Systems (OSS) of Houston, Texas serving as the prime contractor and Stirling Technology Company (STC) of Kennewick, Washington, serving as subcontractor. The contract is in two phases: Phase I Technology Assessment and Phase II Technology Development and Demonstration. Phase I of the project has recently been completed. This paper describes what was done in the assessment, presents the results and makes recommendations.

OBJECTIVE

The objective of the technology assessment was to identify and recommend the key advanced R/F technologies needed to be developed for future Life and Biomedical Sciences spaceflight experiments. An additional goal of the assessment was to satisfy the requirements for all five freezer classifications with the minimum number of technologies needing development.

APPROACH

The basic user functional and vehicle interface requirements were established based on the Space Station Support Equipment U.S. User's Requirements Document [2], Boeing Envelope Drawing Number 683-42003 [3], and Boeing Envelope Drawing Number 683-10043 [4]. Table 1 lists some of the key requirements for each of five freezer classifications.

Table 1 - Key Freezer Requirements

Freezer Classification	Sample Temp. (°C)	Maximum Mass (kg)	Maximum Transient Power (Watts)	Average Power (Watts)	Volume Ext/Int (m^3)
-20°C Storage Freezer	≤-19	100	456	≤200	0.6/0.3
-70°C Storage Freezer	≤-68	269	700	≤200	0.9/0.4
-70°C Freeze Dryer	-70	73	400	≤200	0.3/TBD
-183°C Cryogenic Storage Freezer	≤-183	122.5	245	≤200	0.2/.02
-196°C Cryogenic Quick/Snap Freezer	-196	29.5	180	≤180	.03/TBD

In addition to storing frozen samples, the –20 and –70 °C Storage Freezers must be capable of freezing a 23 °C, 100 ml fluid sample in 45 min. The time between freeze cycles is not stated. The –70 °C Freeze Dryer must be capable of subliming frozen samples at –70 °C in 10^{-3} torr vacuum at a rate of up to one liter of water per day. The Cryogenic Quick/Snap Freezer must be capable of rapidly freezing specimens to –196 °C. It must freeze warm specimens of up to 2 ml volume, in their storage containers, to –196 °C in less than 10 sec, or snap freeze small tissue samples, typically a 5 mm cube, to –196 °C, without cell vitrification, in milliseconds. A general requirement for all freezer classes is for acoustic emissions not to exceed NC-40 specifications.

Moisture management in space storage freezers has been a challenge for systems operating at –20 °C on Shuttle missions. Control of frost build-up in storage freezers operating at much lower temperatures for months or even years will be significantly more difficult, particularly with the Cryogenic Storage Freezer. At its low operating temperature, oxygen in the cabin air will tend to liquefy and deposit within the freezer.

Where necessary, additional functional requirements were derived based on assumed user operational scenarios; i.e. the frequency that warm samples would be placed in the –20 °C and –70 °C Storage Freezers and the maximum sample batch size that the Quick Snap Freezer must be capable of processing without allowing time to recover operating temperature. Performance and design requirements were then derived based on the functional requirements.

A survey was made in four technology categories to identify prospective candidates.

- Coolers
- Insulated Enclosures
- Thermal Transport
- Control Electronics

Vibration/noise and moisture control were also investigated, though without rigorous trade studies or formal analysis.

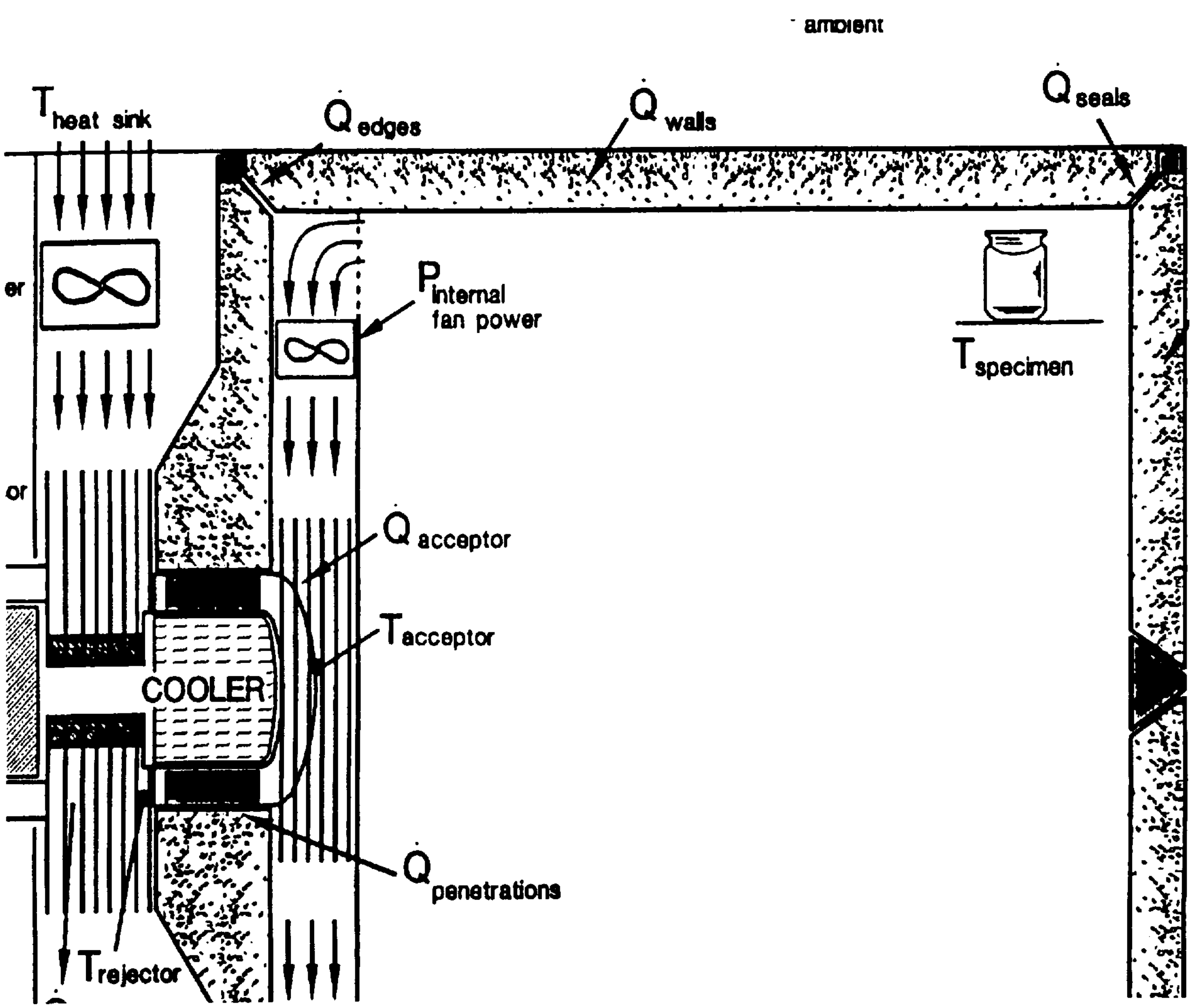
A broad range of applicable technologies was surveyed and the field of more than 40 prospective candidates was narrowed first on the basis of their theoretical capabilities and demonstrated performance, then with more detailed parametric analysis of their capabilities. Characteristics like safety and technological maturity, which cannot be easily quantified, were factored in using a quality function deployment (QFD) analysis. This resulted in five candidates for the cooler subsystem, four for the enclosure, and three for the thermal transport, which were further investigated in a model-based study. Development of electronics for the cooler were judged unnecessary, although simplifying existing space qualified electronics into a lower cost unit was considered desirable. Similarly, development of technology to ensure meeting the NC-40 acoustic emission requirement were judged unnecessary. Although it is a challenge with air heat rejection, it should be possible to meet the noise requirement with off-the-shelf equipment and careful engineering. The candidate finalists in each technology category are listed in Table 2 (The shaded boxes indicate advanced technologies which require technology development).

For every combination of the technologies shown in Table 2, a system was conceptualized for each freezer classification and a thermal model was developed. A generic schematic of the freezer system model is shown in Fig. 1. Both air and water heat rejection were considered. The model seeks to minimize the system mass and power by varying the insulation thickness, while satisfying the internal and external volume constraints. The configuration was then compared to its mass and power specification to determine the margins by which it met (positive margin) or did not meet (negative margin) its requirements. The analysis took into account the specimen heat, the heat load through the enclosure insulation, including panel edge and door seal face conduction, the effects of power consumed by air circulating fans, hot and cold side interface heat exchanger temperature drops, and cooler drive motor electronics. Allowances were made for system structure and mounting.

The system analyses performed show a strong sensitivity to active loads and heat rejection temperatures. The –20 °C system is particularly sensitive to the heat rejection temperature due to the dramatic change in performance for thermoelectric coolers as temperature differentials increase. For the –20 and –70 °C systems, heat rejection at different temperatures was investigated: to 8 °C circulating water, to 23 °C cabin air, and to 40 °C (worst case) cabin air. Other systems were evaluated at a nominal heat sink temperature (23 °C) with the exception of the cryogenic quick/snap freezer which, since it operates in an International Space Station glovebox, necessitates water cooling. Conclusions were drawn about the suitability of the technology combinations for each freezer classification based on both the quantitative systems analysis and the QFD results.

Table 2 - Candidate Subsystem Technology Finalists

Coolers	Enclosure	Thermal Transport
Stirling Cycle	Rigid Fiberglass Panel w/ Metal Skins R-30, ρ = 233 kg/m^3	Copper Conductor k = 398 W/m-°C ρ = 8954 kg/m^3
Turbo Brayton	**Rigidized Polymer MLI Box-in-Box w/ Metal Skins R-60, ρ = 435 kg/m^3**	**Thermal Pyrolytic Graphite (TPG) k = 1200 W/m-°C ρ = 6500 kg/m^3**
Orifice Pulse Tube	**Rigidized Polymer MLI Panel w/ Polymer Skins R-105, ρ = 242 kg/m^3**	Heat Pipes k = 6000 W/m-°C ρ = 4477 kg/m^3
Thermoelectric (-20°C freezer only)	Aluminized Mylar MLI Metal Dewar R-2300, ρ = 155 kg/m^3 (cryogenic freezers only)	
Enhanced Efficiency Stirling		



CANDIDATE SUBSYSTEM TECHNOLOGIES

COOLERS—The candidate coolers fall into two general classes; gas cycles and thermoelectric devices. Coolers requiring use of CFCI, HCFC or other toxic fluids were avoided. Gas cycle coolers, which cool by compressing and then expanding a gas, have two major subdivisions: regenerative, in which gas flow is oscillatory or tidal, and recuperative, in which gas flows continuously in a circuit. Both gas cycle subdivisions have been demonstrated over the temperature range of interest.

Regenerative Coolers—The regenerative cycles with the most promise are the Stirling cycle and the orifice pulse tube. The Stirling cycle coolers have demonstrated the best Coefficient of Performance (COP) of any of the gas cycle coolers. Considerable effort has been expended on their development for sensor cooling in space and for weapon systems. The orifice pulse tube is similar to the Stirling cycle in that it uses a piston to compress and expand the gas within the cycle, and uses a regenerator to separate the cold expansion space from the warm compression space. However, the displacer is replaced by connecting the cold space with a tube and through an orifice to a gas reservoir. This arrangement causes cyclic pressure variations, similar to Stirling coolers, which produce a cooling effect, but without moving parts on the cold end of the machine. Demonstrated pulse tube COP tends to be lower than Stirling coolers. The performance divergence increases as temperature increases. Pulse tube coolers are improving rapidly and their performance at low cooling temperature is approaching Stirling.

It is possible to conceive of technology improvements to a Stirling cooler, such as a low thermal loss expander housing, advanced regenerators, and improved cooler to storage volume heat transfer interface, which would provide 14 percent greater efficiency than that demonstrated in current Stirling coolers. An additional 25 percent efficiency gain also appears to be possible through design innovation to improve motor efficiency. An enhanced efficiency Stirling cooler, with overall 39 percent improvement in COP over the current Stirling coolers, is included as a candidate cooler in the trade studies.

Recuperative Coolers—The recuperative cycles include positive displacement and turbo Brayton machines. Only the turbo Brayton cycle is considered sufficiently mature for space freezer applications. Stirling and pulse tube coolers produce a localized cold surface which must be carefully interfaced to the cooling load, to avoid excessive temperature drops and reduction in effective COP. In contrast, the Brayton cycles circulate cooling gas directly to the load, allowing much more freedom in the heat exchanger design, without affecting cycle performance.

Thermoelectric Coolers—Thermoelectric (TE or Peltier) coolers use solid state devices to lift heat. They are relatively compact and light-weight. Although they have low vibration, high expected reliability, and reasonable technology maturity, the COP of TE coolers restrict the feasible acceptor temperature and heat lift capacity of these systems. The maximum feasible temperature differential is in the range of 50 to 75 °C. Demonstrated TE two-stage technology is a candidate for the –20 °C storage freezer but is impractical for the other four freezer classifications.

Figure 2 compares the coefficient of performance (COP) of the cooler candidates. The COPs used in the analysis were based on curve fits of the best published performance data for each candidate technology normalized to 35 °C heat rejection temperature. The Carnot COP (the theoretical limit) is also shown for reference. Due to the limited amount of data available for the pulse tube, turbo Brayton, and enhanced Stirling, their COPs were set at a fixed ratio to the Stirling COP:

$$COP_{Brayton}/COP_{Stirling} = 0.67 \qquad (1)$$

$$COP_{Pulse\ Tube}/COP_{Stirling} = 0.5 \qquad (2)$$

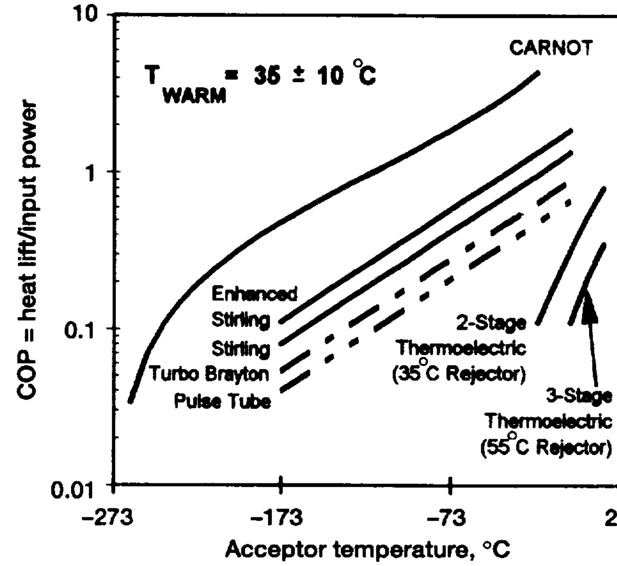


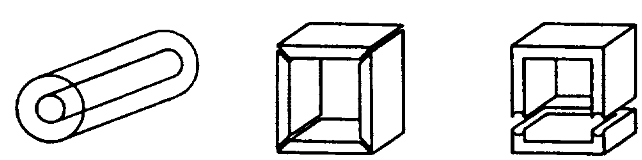
Figure 2.—Candidate cooler performance.

$$COP_{Enhanced\ Stirling}/COP_{Stirling} = 1.39 \qquad (3)$$

ENCLOSURE—The enclosure technologies needed for the five freezer classifications were considered in two broad categories: cylindrical dewars and rectangular cabinets. Although a dewar can have a very high thermal resistance, a cabinet provides greater internal volume for a given external envelope. To meet the specifications for –20 and –70 °C storage freezer internal volumes, a cabinet construction is essential. In addition to the volumetric efficiency, the dewar and cabinet constructions have different structural weight, technological maturity, thermal resistance, materials safety, access ease, and complexity/reliability. Figure 3 illustrates the configurations for dewar and cabinet construction, for the enclosure technology candidates considered.

Cylindrical Dewars—Current technology cylindrical dewar construction (Fig. 3(a)) has the greatest thermal resistance (R-2000 to R-3000). The high vacuum ($<10^{-3}$ torr) between the inner and outer walls of the pressure vessel eliminates gas convective and conductive heat transfer; the aluminized mylar multilayer insulation (MLI) reduces radiative heat transfer; and, since the inner and outer shells are generally only joined at the access port region, there is minimal conductive heat transfer.

The internal volume requirement for the two cryogenic temperature freezers includes the range in which dewar weights are reasonable and their equivalent insulation density is much less than for panel insulation. The high thermal resistance of the dewar is required to limit the heat leakage across the temperature difference of approximately 220 °C (room temperature to –196 °C). In contrast, the –20 and –70 °C freezers are volume and weight critical,



(a) Dewar. (b) Panel. (c) Box-in-box.

Figure 3.—Enclosure construction configurations.

precluding the dewar construction. For these freezer classifications, the rectangular cabinet construction is needed.

Rectangular Cabinets—Two qualitatively different cabinet vacuum insulation constructions are considered: the panel (Fig. 3(b)) and box-in-box (Fig. 3(c)). The box-in-box has inherently greater thermal resistance since it minimizes the number of seams, which are the leading conduits for heat leakage. Metal skinned panels offer cost and design benefits, but edge losses significantly reduce their potential thermal resistance performance. Plastic skinned panels would minimize edge loss but must be non-porous enough to sustain a vacuum for ten years or longer. Despite their low mass, foam insulation materials are considered to be impractical, because of their low R values (typically ranging from R-5 to R-7 per in.).

A variety of low and moderate vacuum insulation panels, filled with powders or fiberglass and having plastic or metal skins have been developed. The demonstrated enclosure R values for these current technology panels range from R-15 to R-35. An insulation value of R-30 was used for the analysis as a representative of these "state of the art" (SOA) insulation panels. OSS is currently developing a polymer panel which should address the major shortcomings of SOA vacuum panels. It features rigid polymer MLI with integral low conduction vacuum support. Edge losses are minimized by making the skins out of a polymer which has a hundredfold reduction in thermal conductivity compared with stainless steel. The calculated average insulation value for these panels is R-105. Box-in-box construction with polymer skins will further reduce edge losses and in combination with rigid MLI vacuum support is expected to yield an average insulation value of R-150. With metal skins and box-in-box construction, rigidized MLI is expected to have an average insulation value of R-60.

THERMAL TRANSPORT—The different candidate cooler technologies have unique thermal interface requirements. To evaluate the advantages and drawbacks of the alternative transport technologies, the contractor team developed conceptual designs of several cooler/enclosure combinations. The thermal transport technologies were then used to interface the cooler/enclosure technologies with the cooled volume and the heat rejection sink to meet the published freezer specifications. The three classes of thermal interface technologies evaluated are: metallic conductors, carbon conductors, and heat pipes.

Metallic Conductors—Metallic conduction strips, especially copper and aluminum, though simple and effective, are relatively heavy and sustain a significant temperature drop along their length. This temperature drop causes the cooler to operate at reduced temperature with lower COP, and requires more power. Copper has better thermal properties than aluminum and, since only small quantities are required by the conceptual design, its weight penalty compared with aluminum was minimal. Copper was selected as the baseline metallic conductor for this study.

Carbon Conductors—Carbon conductors are a newer technology used in military avionics cooling systems, but they have not been widely applied elsewhere. One particular material, Thermal Pyrolytic Graphite (TPG), has been developed into planar configurations and provides a lower mass and lower thermal resistance relative to the metallic systems. The TPG is chemically vapor deposited graphite layers encased in aluminum or copper. It is anisotropic in bulk; how this will effect its design usefulness is not yet clear.

Heat Pipes—Heat pipes are an established technology that provides a near isothermal, high heat flux thermal transport media. In a heat pipe, a 2-phase working fluid is used to transport heat across relatively long paths with minimal temperature drop and no moving parts. Since the working fluids tend to be toxic and may exert relatively high pressure at room temperature, double containment may be required to ensure crew safety. This could impact the heat transfer efficiency.

ANALYSIS RESULTS

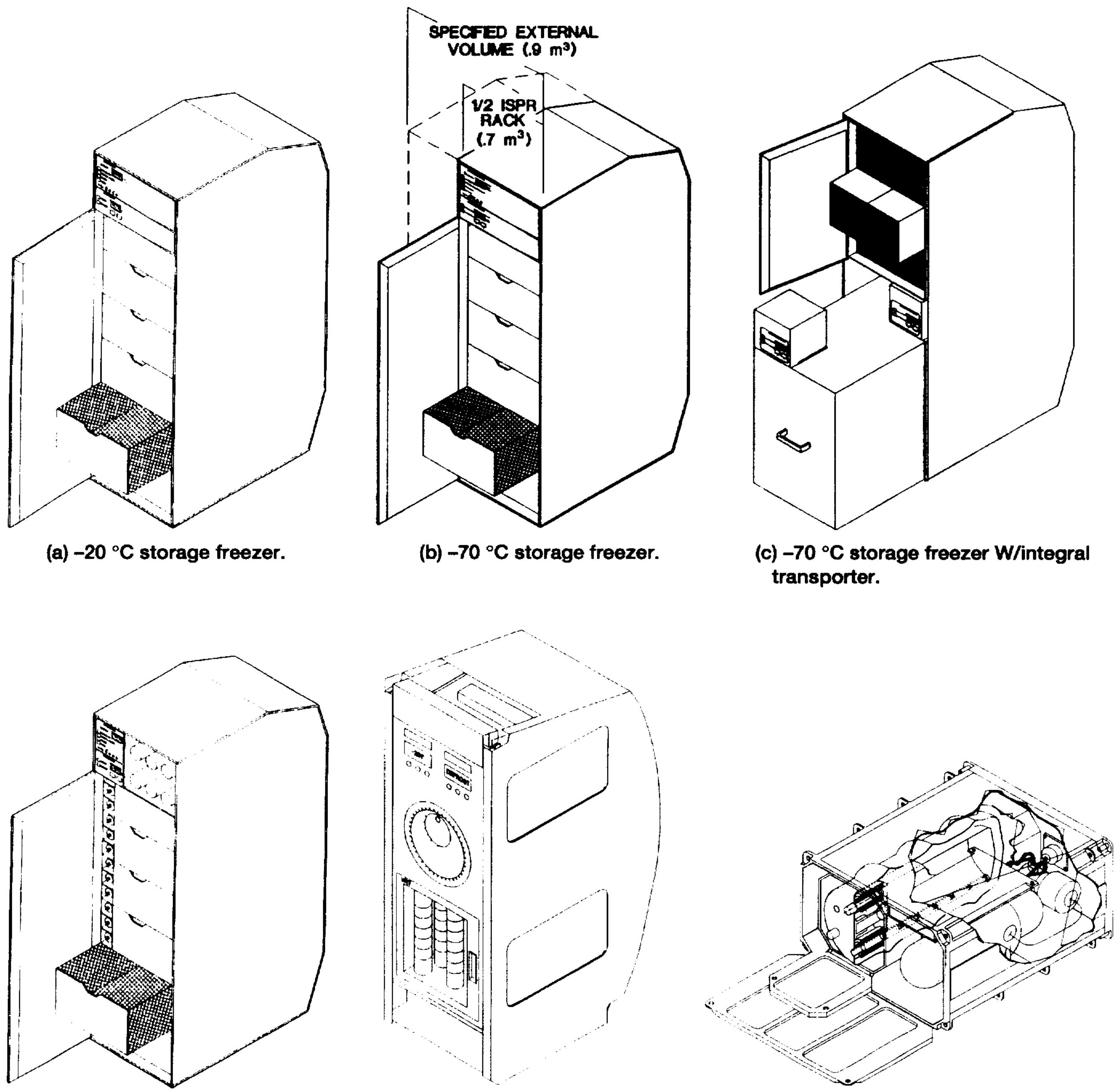
The following are the results of the system analysis. Concept drawings of each of the five freezer classes are shown in Fig. 4.

–20 °C STORAGE FREEZER—The worst case condition for the –20 °C Storage Freezer (Fig. 4(a)) is heat rejection to 40 °C air heat sink, 55 °C heat rejector temperature, and freezing a 100 ml sample in 45 min with a duty cycle of 3 (3×45 min = 135 min/cycle). The analysis results indicate that the power requirement can be met with any of the possible combinations of enclosure, and thermal transport technologies with Stirling and Brayton coolers, by 45 to 55 percent and 20 to 45 percent margins respectively, and for five of the six combinations with pulse tube cooler, with 0 to 12 percent power margin. Only the combinations with a Stirling cooler with R-30 and R-105 had positive mass margins of under 5 percent. All technology combinations with a thermoelectric cooler were 120 to over 200 percent above the 200 W average power requirement and 10 to 40 percent above the 100 kg mass requirement.

With cabin air cooling under normal conditions (20 to 25 °C) and a sample freeze duty cycle of 3, the thermoelectric option is viable if the best panel insulation (R-105) is developed. With the duty cycle increased to 1, the TE system is again unable to provide positive mass and power margins. Only combinations with Stirling coolers have small (<5 percent) positive mass margins.

For the case with 8 °C water cooling, all technology combinations considered were able to easily meet the power requirement, but narrowly meet the mass requirement. Only those combinations which included R-30 or R-105 insulation have small (<6 percent) positive mass margins. In conjunction with the systems analysis, a QFD analysis was done to compare the feasible design solutions for each of the three best coolers. When all the requirements are factored in, a thermoelectric cooler with TPG heat transport and R-105 insulation was deemed the best candidate overall, if system heat rejection is to 8 °C cooling water. In the qualitative analysis, the advantages in safety, vibration tolerance, vibration production, reliability, and compact design overcome the efficiency and mass shortcomings.

–70 °C STORAGE FREEZER—The modeling results for the –70 °C Storage Freezer system (Fig. 4(b)), with worst case air heat rejection and a duty cycle of one, failed to identify any configuration using the pulse tube, Brayton cycle, or reference Stirling cycle coolers that met all of the specifications. Current technology pulse tube coolers operating in this temperature range are not efficient enough for this challenging case. The Brayton cycle coolers are also unacceptable but, with reduced active loads, could be utilized with the advanced insulation. With the more aggressive 1 duty cycle active thermal loads, the reference Stirling cycle shows negative power margins of nearly 20 percent with the best insulation and thermal transport technologies. An



(a) –20 °C storage freezer.
(b) –70 °C storage freezer.
(c) –70 °C storage freezer W/integral transporter.
(d) –70 °C storage freezer W/freeze dryer.
(e) –183 °C storage freezer.
(f) –196 °C quick snap freezer.

Figure 4.—Freezer systems concepts.

enhanced Stirling cycle, with 39 percent efficiency improvement over demonstrated Stirling cycles at –80 °C, in combination with advancements in insulation technology (R-60 or better), appears feasible.

With the sample freeze duty cycle increased to three, the reference Stirling cooler appears feasible with R-60 insulation technology, believed to be producible with minimal technology development.

Under less severe conditions with a 23 °C air heat sink, power margins increase on all systems with the potential to use a broader range of cooler technologies (i.e., Brayton cycle with heat pipe and advanced TPG thermal transport and R-105 insulation).

If a water bus were available for heat rejection, power margins would again increase, however not as dramatically as for the –20 °C Freezer system. This is because the change in COP for Stirling, pulse tube, and Brayton cycle coolers is not as sensitive to temperature differentials as the thermoelectric cooler COP. Mass margins are consistently positive indicating sufficient mass allocation. Under these conditions, the system model makes full use of the external volume available to minimize the system power required; this results in insulation thicknesses of ~8 cm (3.1 in.).

Methods to maintain the samples below the –68 °C maximum temperature during power off were explored. Samples would have to be cooled 10 to 15 °C below their steady state temperature before the power interruption to survive for 12 hr without power. The added burden for subcooling the –70 °C system requires an additional 20 to 30 W of power (10 to 15 percent of budget).

Weight and power margins decrease in every case, compared to results for the powered mode.

The –70 °C freezer mass limit is 269 kg. This makes it impossible to use as a transport locker without special handling equipment. A second design excursion explored the possibility of detaching part of the storage volume from the cooler for transportation as a smaller unit appropriate to the Mini-Pressurized Logistic Module (MPLM) and light enough for single person handling (32 kg). Figure 4(c) shows a conceptual design of this system. This option is contingent upon design of a thermal transport system which can cleanly and simply detach from the enclosure and then reseal the volume to minimize heat and moisture entry. Both are considered manageable problems, but this transporter design may force the selection of certain thermal transport technologies over others. In order to achieve the very low weights for the transporter, enclosure wall thicknesses are small, stressing the performance of the cooler. Although most candidates are eliminated if a 32 kg transporter is required, the enhanced efficiency Stirling cooler coupled with the R-105 insulation can still meet specifications with 30 to 40 percent power margins. It is also possible that the transporter module could operate at either –70 or –20 °C, thus allowing greater flexibility in on-orbit freezer configuration and maximum utilization of available equipment rack space.

A third excursion on the –70 °C storage freezer began with the observation that the R-105 material and enhanced efficiency Stirling produced sufficient benefits that the system might be consolidated into a smaller unit. A design study did reveal a feasible half-rack (0.7 m^3 exterior volume compared to the specified 0.9 m^3) design based on these advanced technologies as shown in Figure 4(b).

–70 °C FREEZE DRYER—The modeling results for the –70 °C Freeze Dryer (Fig. 4(d)) show that every case, except the relatively inefficient pulse tube cooler coupled with the lowest R value insulation, could meet the weight and power budgets handily. The enhanced Stirling was not considered necessary to include in this analysis. The QFD analysis, nonetheless recommends the use of the higher R value insulation to relieve other system variables.

The large margins suggest that meeting the requirements is not challenging. Since samples are placed in the freeze dryer already frozen to –70 °C, the drying process can proceed slowly with minimal power.

–183 °C CRYOGENIC STORAGE FREEZER—Figure 4(e) is a conceptual design of a cryogenic storage freezer. The concept assumes that samples are introduced into the storage volume already at cryogenic temperatures, presumably frozen in the quick/snap freezer, so that the active heat load is minimal. The modeling results show plenty of design margin for the system, so much so that the QFD analysis points to a relatively inefficient pulse tube-based design because of its additional advantages in vibration isolation and reliability.

The system design presumes an MLI dewar using aluminized mylar at 35 layers/cm. In the system analysis, the insulation thicknesses were kept below 5 cm to minimize detrimental compacting of the layers under launch vibrations. Such compaction would degrade its insulating properties.

Modelling did reveal that certain heat leaks which are relatively unimportant in higher temperature freezers, for example around wire penetrations, become important in this system. Lay up of MLI around the penetrations must be carefully designed to minimize radiation tunneling. Although not essential for system performance, development of polymer conduits for wall penetrations would greatly improve packaging and cost, replacing the welded metal bellows penetrations that are conventionally used. Access into the freezer is also a major source of heat transfer. The opening cover, nominally an evacuated stainless steel or foam plug, must be deep in order to minimize conduction. The deep plug makes packaging and access more difficult. An evacuated polymer plug, similar in construction to the R-105 panels considered for the enclosure, would reduce this cumbersome length.

Condensation is a problem not only for water vapor, but also for oxygen which may condense from cabin air at temperatures below the –183 °C maximum operating temperature. This problem is exacerbated when further subcooling is required to address unpowered time, such as during specimen transportation. Analysis shows that the volume would have to be subcooled 5.5 °C, which is not a problem for the cooler or enclosure. The system design would have to incorporate a nitrogen purge to keep out ambient air and preclude liquid oxygen (LOX) buildup. The International Space Station will have dry nitrogen available as a utility; Shuttle or Mir usage would require a gas supply be brought along. Since no door openings are planned during transport, no nitrogen is required during transport operations.

–196 °C CRYOGENIC QUICK/SNAP FREEZER– Figure 4(f) is a conceptual design of a Quick/Snap Freezer. It relies on intimate contact between the specimen and a large cold thermal mass of a highly conductive material, such as copper, to rapidly freeze the specimen. The frozen specimens are then placed in small pre-cooled sealed vials, which can be stacked end to end until the row is filled, and then transferred as a unit in a carrier into the –183 °C storage freezer. The requirements documents did not specify the rate at which samples must be processed. The analysis assumed a worst case of ten specimens every four hours. Although the results of the modeling with air heat rejection at 40 °C cabin air (55 °C rejection temperature) show that only a few options exist which can accommodate this rate, a lower use rate would permit many more design options. The most likely operating environment for the Quick/Snap Freezer would be in a glovebox, with water heat rejection. The systems analysis for the water heat rejection case shows an increase in power margins of about 20 to 50 percent, over the air heat rejection case, depending on cooler technologies. For the enhanced Stirling cycle, this represents an increase in specimen processing rates (i.e. quick freezing of 2 ml specimens) of approximately 33 percent. The QFD analysis points to the highest technology combination as being most appropriate for this application because it also allows more design and operational flexibility.

Since nitrogen liquifies at –196 °C at one atmosphere pressure, a substitute for nitrogen would have to be used as a purge gas, or perhaps the nitrogen gas could be mixed with helium. Alternatively, the science community could be petitioned for a few degrees relief on the temperature specification. The –196 °C temperature was selected because it is the temperature of the liquid nitrogen used to cool the snap freezer on earth. Since liquid nitrogen is not available in space, a cryocooler is required to precool the conductive block. Relief of the temperature specification by even a few degrees would greatly simplify condensation control.

CONCLUSIONS AND RECOMMENDATIONS

FREEZER SYSTEM CONCLUSIONS—The trade studies presented in the previous section included technologies which are not yet within the demonstrated state of the art. These are the enhanced efficiency Stirling cycle cooler, polymer panel enclosures, and thermal pyrolytic graphite heat transport. Table 3 summarizes the recommended freezer technology combinations which will meet the requirements for each of the five freezer classifications (shaded boxes indicate advanced technologies needing development). For four of the five freezer classifications, the systems analysis identified at least one combination of cooler, enclosure, and thermal transport technology which meets the requirements for mass, power, and volume without major technology development. In the case of the –70 °C storage freezer, it requires insulated enclosure and thermal transport technology development to meet the power requirements, and the QFD analysis points to the use of more developmental technologies to mitigate problems with the other requirements. Having these technologies available would provide more design and operational options. Use of advanced technology will decrease power consumption and heat rejection, reduce mass and possibly, the rack space required. It also should reduce the crew time for maintenance, improve freezer reliability, and lead to lower operational cost.

TECHNOLOGY CONCLUSIONS—Nine technology development areas were identified as having potentially important impacts on the performance of the various freezer classifications, their design margins, and/or their operational flexibility. Some also have commercialization potential.

Polymer Panel Insulation—A polymer insulation panel is comprised of rigid plastic multilayer insulation with integral vacuum support structure, encased in plastic skins which can maintain a high ($<10^{-3}$ torr) interior vacuum for >10 years. The panels would be used to construct a rectangular cabinet with a calculated average insulation value of R-105 with edge losses included. This represents a significant improvement over the currently available steel-skinned vacuum panels that have demonstrated R-30 cabinet insulation values. Their density is expected to be only slightly higher (4 percent) than the steel skin panels. However, cabinets using the welded steel skin panels must be reinforced to prevent flexing the welds. Cabinets made with the polymer panels are expected to require little or no reinforcing, and may have lower mass than the steel skin cabinets.

The –70 °C freezer classification benefits most from the polymer vacuum panel enclosure since the system analysis indicates the –70 °C specifications were unlikely to be met without advanced technology. The –20 °C storage freezer and –70 °C freeze dryer would also be lighter and more power efficient with this technology. An MLI dewar augmented by similar plastics technology for wire penetrations and the entry opening could reduce the weight and power needs of the cryogenic designs.

The key development challenges in the polymer vacuum panel technology are: (1) selecting a material with the strength, low mass, and low thermal resistance needed, which is also capable of supporting and maintaining a high vacuum, and (2) sealing the outer skin edges to maintain the required high internal vacuum. If these panels could be produced economically in quantities, they would have the potential for application in commercial and industrial insulation systems across a broad temperature range (150 to –196 °C).

Enhanced Efficiency Stirling Compressor Motor—To improve the efficiency of a Stirling cycle cooler, improvements in drive motor efficiency can be sought. A higher strength permanent magnet could be used. Square wire could be used in the coil windings to minimize coil size and resistance losses. A careful trade-off between moving magnet, moving coil, and moving iron design options should identify the most efficient option. The reference compressors are the high efficiency commercial systems from Stirling Technology Company (STC) and Sunpower Inc. systems. The calculated efficiency improvements represent a 15 to 20 percent reduction in the power required to accomplish the required compressor work. This approach is an incremental

Table 3 - Recommended Freezer Technology Combinations

Freezer Classification	Cooler	Enclosure	Thermal Transport
-20°C Storage (Space Station) (water cooling)	Thermoelectric	Rigidized Plastic MLI Polymer Panel (R-105)	TPG
-20°C Storage (Shuttle or MIR) (air cooling)	Stirling	Fiberglass with Metal Skin Panel (R-30)	Copper
-70°C Storage	Enhanced Stirling	Rigidized Plastic MLI Polymer Panel (R-105)	TPG
-70°C Freeze Dryer	Stirling	Fiberglass with Metal Skin Panel (R-30)	Copper
-183°C Cryogenic Storage	Stirling	MLI Dewar (R-2300)	Copper
-196°C Cryogenic Quick/Snap	Enhanced Stirling	MLI Dewar (R-2300)	Copper

improvement on proven technology to realize efficiency gains at relatively low risk and cost.

Thermal Pyrolytic Graphite (TPG) Cold Finger—The cold head of the Stirling cooler is a concentrated cold spot to which the entire cabinet heat load must be interfaced. Conductive heat distribution produces a temperature drop across the heat exchanger which must be minimized to improve the system efficiency. TPG is a solid conductor with conductivity and density properties superior to metallic conductors such as copper or aluminum. A TPG cold finger could provide a lower temperature drop from the stored specimen to the cooler acceptor surface. Since air convection heat transport requires a larger surface, the lower density and higher strength of the TPG should permit a greater range of design options with TPG than with metallic conductors. TPG is formed by hot isostatically pressing sheets of the planar material inside a form fitting aluminum or copper can which becomes a permanent part of its structure. Because of its heterogeneous composition and its inherent anisotrophy, TPG designs must be carefully considered to take full advantage of its properties.

Insulating Pressure Vessel—Stirling cycle coolers have a parasitic conduction heat leak through the expander pressure vessel which separates the coldest (acceptor) and warmest (rejector) temperature surfaces. The Stirling coolers normally use a stainless steel enclosure to form the helium tight pressure vessel. A plastic pressure vessel, with a lower thermal conductivity, would reduce this unwanted heat transfer by thermally isolating the acceptor and rejector ends of the device. An additional benefit of this configuration is the reduction of the back heat leak when the system is not operating.

There are several challenges in this technology, especially the metal-to-plastic seal, the helium containment quality and the possible contamination of the cold heat exchange surfaces or the regenerator by plastic outgassing. The commercial potential of this technology is related to the efficiency benefits this technology offers to Stirling and pulse tube cooler systems.

Vacuum Dewar Compatible Polymer Interfaces—Dewar enclosures must include penetrations for utility runs and sensor wires. Existing implementations use welded metal bellows that join the inner and outer vessel walls, forming a low conduction path through the pressure vessel. Replacing the bellows with plastic components bonded to the pressure vessel housing could reduce the component cost of the dewar assembly and lower the conduction heat loss through the penetration. The key technical challenge is the vacuum tight, long life, metal-to-plastic bond which can endure the temperature excursions expected in the dewar operations. Commercial potential for improved performance and lower cost dewar assemblies would be in the laboratory equipment and cryogenic materials processing industry.

Brush Carbon Quick Disconnect—The ability to quickly disconnect the cooler, heat exchangers, and enclosure would support the removal of a lightweight enclosure from the rack assembly either on the ground, after landing or for transport by an MPLM. It would also facilitate on-orbit maintenance of cooler and heat exchanger assemblies. A high conduction breakable contact is based on a proprietary brush carbon material. Brush carbon is a velvet mat of carbon fibers which has low thermal resistance only when mated. It also accommodates low contact pressures and high mechanical compliance to allow for the thermal expansion of dissimilar materials and potential vibration isolation of the cooler surfaces. Brush carbon has been demonstrated on the ground but concerns over carbon fiber contamination need to be addressed for use in space. Also of concern is the control of condensation and moisture build-up on the cold plate surface if an unsealed brush carbon assembly was exposed to the atmosphere.

A brush carbon contact could also be incorporated into a thermal switch which could permit sharing of the cooler acceptor between the –70 °C freezer and the freeze dryer by selecting a contact conduction position.

The key development challenge, beyond verifying the properties of brush carbon, is the resolution of the life and contamination safety issues related to the release of broken carbon fibers. The commercial product applications of this technology could include more maintainable heat exchanger and low vibration heat exchanger applications, and long life thermal switches.

Low Noise Heat Rejector—The acoustic emissions of the system must be controlled to very low levels (NC-40 with a goal of NC-30). With the air heat rejection media, the heat exchanger must produce the minimum delta temperature across the fins to minimize the temperature of the heat rejection surface. Previous space freezers, based on military standard fans and metal finned heat exchangers, have not met the acoustic requirements. Improving heat exchanger efficiency with TPG should enable lower air velocity heat transfer, thus requiring a lower fan speed which would minimize the acoustic noise emitted directly from the fan and air flow turbulence.Low noise heat exchangers have many potential applications such as computer work stations and office equipment.

Phase Change Panels—The –20, –70 and –183 °C storage freezers are required to maintain samples at or below the specified temperature during power-off conditions. For the –20 and –70 °C systems, incorporating a phase change material (PCM) inside the freezer would eliminate the need for significant subcooling before power off while permitting the freezer to maintain the specified temperature for an extended or unplanned power-off condition. PCM would also reduce the temperature variations caused by sample freezing and door opening heat loads, allowing the freezer and heat exchanger systems to be sized more closely to average instead of peak loads. PCM could be incorporated into structural components with minimal impact on net freezer weight. A potential PCM for the –70 °C freezer is a hexane-octane blend tailored to have a phase change temperature several degrees lower than the operating temperature to allow for heat transfer through the containment. The key technical challenge is in the containment of the PCM, since the double or triple containment needed for safety will result in poor heat transfer and heavier assemblies. The –20 °C freezer temperature phase change technology is under development for commercial and industrial cooling load management systems. A commercial use for the lower temperature phase change materials technology has not been established at this time.

Moisture Management—Moisture and condensation management is especially needed for the –20, –70, and –183 °C storage systems, which will be operating continuously during extended missions. Ground-based systems which rely on gravity to transfer moisture during periodic defrost cycles are not applicable to space. The system level approach to moisture management would include: reducing the moisture load introduced into the freezer, capturing any moisture which gets inside, and eliminating the moisture from the enclosure with a minimum of crew workload.

The challenge is to provide a reliable and robust moisture management system with minimum mass, power, and crew maintenance time. Desiccants and cold traps must be further evaluated to determine the expected performance at reduced temperatures, and their employment configured to minimize the crew involvement.

TECHNOLOGY DEVELOPMENT RECOMMENDATIONS—Table 4 compares the thermodynamic benefit, maturity, and development risk of the nine-technologies discussed and also indicates how many of the five freezers benefit from the technology. In the cases of the brush carbon quick disconnect, low noise heat rejector, and the moisture control system, the thermodynamic benefit is minimal, but operational or maintenance benefits may be significant.

Development and demonstration of polymer panel insulation with an enclosure R-value of 105 would have a significant impact on space freezer designs. The –20 °C systems would comfortably be able to accommodate higher heat rejection medium temperatures, such as warm air, and both the –20 °C and the –70 °C systems would be configurable to transportable storage lockers that can be handled by a single person in a 1 g environment. If subcooling is required, the –70 °C storage locker would not require an advanced cooler. Such panels would have applicability outside the requirements addressed in this study, for example in domestic refrigerators and even in commercial systems. The conclusion of this analysis is that plastic panel technology has the highest leverage and should be given highest priority for development.

Enhanced efficiency Stirling coolers also have leverage across several freezer classifications. Although thermoelectric and pulse tube coolers have vibration and reliability advantages, current Stirling cycle coolers are so much more efficient as to be competitive in spite of these advantages, and an enhanced efficiency Stirling would allow still more design margin which could be returned to the spacecraft integrator as unused power or mass to be distributed to other challenged systems. Enhanced efficiency Stirling coolers could impact all five of the freezer classifications and help enable the –70 °C freezer/freeze dryer combination. It, too, is a high leverage technology.

Calculation suggests that cooler efficiency could be improved by a total of 39 percent if all the improvements discussed were included. Twenty-five percent of that would be attributable to engineering re-optimization such as stronger magnets, which need not be demonstrated in a technology development program. The use of an insulating pressure vessel should make up the remaining fourteen percent. The goal for the pressure vessel is thus established to be 14 percent COP improvement above the stainless steel baseline.

Replacing metal conductors or heat pipes with TPG would improve the performance, safety, and/or reliability of virtually any system, making this a technology with good leverage. However, the system level improvement would be relatively modest compared to R-105 enclosures or cooler efficiency enhancement. A good risk management strategy would invest a moderate amount of resources in TPG development for whatever improvement it can provide. Metallic conductors typically show a 20 °C temperature drop between the cooler cold head and the enclosure air. Calculations suggest TPG could reduce this drop to 10 °C, which would allow a 10 percent improvement in cooler system COP, over baseline copper conductors. The 10 °C temperature drop is established as the goal for technology development.

Table 4 - Technology Benefits, Maturity and Risk

Technology Candidate (By Priority)	**# of Freezers Benefited**	**Thermodynamic Advantage (dW/W %)**	**Technology Maturity**	**Risk**
1. Rigid Polymer Panel MLI	3	55	Medium	Low
2. LCP Cooler Pressure Vessel	5	7	Medium	Medium
3. Moisture Management	4	5	Medium	Low
4. TPG Cooler Cold Finger	5	12	Medium	Medium
5. Brush Carbon Quick Disconnect	5	N/A	High	High
6. Low Noise Heat Rejection	5	N/A	High	Medium
7. Phase Change Panels	4	11	Medium	Low
8. Vacuum Dewar Polymer Interfaces	5	3	Medium	Medium
9. Stirling Cooler Motor Efficiency Improvements	5	17	High	Low

During the Technology Assessment, the contractor team performed preliminary design analyses to develop concept configurations to meet the volume, power and thermal performance specifications for all five freezer classifications. The team recommendations for the brassboard system development are based on the preliminary analysis and designs for the -20 and -70°C Storage Freezers. However, acoustic emissions technology is pertinent to any freezer classifications where the cooler must reject heat to the cabin air. The recommended acoustic technology development activity is to demonstrate that the NC-40 (with a goal of NC-30) acoustic emissions can be satisfied in a dimensional mockup of the air rejector. The heat exchanger geometry and projected thermal performance is to be based on the use of advanced Thermal Pyrolitic Graphite (TPG) materials to enable the lowest fan power and flow velocities.

The validation of the TPG materials for the acceptor heat exchanger will be used to predict the rejector heat exchanger requirements. The recommended development plan does not include the manufacture and test of a functional air heat rejector. To conserve resources, it is recommended that the liquid cooled Stirling cooler produced by STC under Small Business Innovative Research (SBIR) funds be used for the brassboard cooler. This cooler will not be subjected to acoustic emissions and vibration testing and verification.

The air rejector exchanger mockup test will incorporate axial fans, low noise heat exchanger geometry, and representative duct work. This subsystem will demonstrate sufficient air mass flow rates with the required heat transfer within acoustic design limits.

An advanced moisture and condensation management approach would also have leverage over several systems. Although this conclusion doesn't emerge directly from the thermodynamic performance, operational and maintenance needs highlight it as an area requiring a solution. The freezer requirements specify that maintenance activities be limited to 2.6 man hr/year. Apportioning about half of his maintenance time to moisture control, the goal for this technology would be to accomplish any condensate removal in less than 10 man min./month, while remaining within the weight, power, and volume allowables for the system. Lower priority improvements, like phase change material and brush carbon, though low leverage, are attractive enough to warrant further investigation at a modest level, especially if it can be done in the context of other systems demonstrations.

Although this technology assessment indicates that, under normal operating conditions with water or cabin air heat rejection, most of the user requirements for the Life and Biomedical Sciences freezer classifications can be met using current technology, significant benefits can be realized through development and implementation of advanced technologies recommended here. Through use of these advanced technologies, system mass, power consumption, and heat rejection can be reduced. The freezer systems will have greater latitude in addressing power off conditions, specimen freeze duty cycles, or changes in Shuttle or Space Station utility user allocations and operating condition. Flexibility in storage operating temperatures would provide better utilization of available rack space, allow mission configuration flexibility, and provide a means to simplify specimen transport and equipment maintenance logistics. The technology development priorities enumerated in this paper provide guidance to the best return for available resources to provide the advanced technology needed to support future Life and Biomedical Sciences space missions.

Further information about the R/F Technology Assessment can be found in reference [5] which will be published mid 1996.

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The NASA Lewis Research Center, through contract with Oceaneering Space Systems, is engaged in a project to develop advanced refrigerator/freezer (R/F) technologies for future Life and Biomedical Sciences space flight missions. The first phase of the project, a technology assessment recently has been completed to identify the advanced refrigerator/freezer technologies needed and best suited to meet the requirements for the five R/F classifications specified by the researchers, to rank those technologies based on benefit and risk, and to recommend those which can be developed within this project. This paper presents the basis, the methodology, and results of the R/F technology assessment, and makes recommendations for the technology areas to be developed.

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